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Efficiency of soil and water conservation practices in different agro-ecological environments in the Upper Blue Nile Basin of Ethiopia

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Abstract: In developing countries such as Ethiopia, research to develop and promote soil and water conservation practices rarely addressed regional diversity. Using a water-balance approach in this study, we used runoff plots from three sites, each representing a different agro-ecological environment, e.g., high, mid and low in both elevation and rainfall, in the Upper Blue Nile Basin of Ethiopia to examine the runoff response and runoff conservation efficiency of a range of different soil and water conservation measures and their impacts on soil moisture. The plots at each site represented common land use types (cultivated vs. non-agricultural land use types) and slopes (gentle and steep). Seasonal runoff from control plots in the highlands ranged 214–560 versus 253–475 mm at midlands and 119–200 mm at lowlands. The three soil and water conservation techniques applied in cultivated land increased runoff conservation efficiency by 32% to 51%, depending on the site. At the moist subtropical site in a highland region, soil and water conservation increased soil moisture enough to potentially cause waterlogging, which was absent at the low-rainfall sites. Soil bunds combined with *Vetiveria zizanioides* grass in cultivated land and short trenches in grassland conserved the most runoff (51% and 55%, respectively). Runoff responses showed high spatial variation within and between land use types, causing high variation in soil and water conservation efficiency. Our results highlight the need to understand the role of the agro-ecological environment in the success of soil and water conservation measures to control runoff and hydrological dynamics. This understanding will support policy development to promote the adoption of suitable techniques that can be tested at other locations with similar soil, climatic, and topographic conditions.

Keywords: agro-ecology; drought-prone; runoff coefficient; runoff conservation efficiency; Ethiopia

1 Introduction

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Over the last three decades, the government of Ethiopia and a consortium of donors have invested substantial resources to develop and promote sustainable land management practices as part of efforts to improve environmental conditions, ensure sustainable and increased agricultural production, and reduce poverty (Herweg and Ludi, 1999; Nyssen et al., 2000; Kassie et al., 2009; Adgo et al., 2013; Adimassu et al., 2014; Amare et al., 2014; Haregeweyn et al., 2015, 2017). Some of the major physical soil and water conservation techniques being used in the country include short trenches, soil and stone bunds, cut-off drains, check dams, hillside terraces, area closures, *Fanya juu* (a Swahili word meaning 'throw uphill'), and *Zai* pits (a term in Burkina Faso used to refer digging pits that retain compost and direct water into the soil surrounding each plants to grow). Recently, physical structures have been combined with biological measures such as vegetation establishment to protect the soil against erosion (Amare et al., 2014). But despite these efforts, the sustainability of the development work is unclear. Due to low rates of adoption, most of the promoted practices have been only partially successful. In some cases, disadoption or reduced use of the techniques has been reported (Tadesse and Belay, 2004).

Past efforts to develop and promote soil and water conservation practices had neglected the pronounced regional diversity of Ethiopia. Haregeweyn et al. (2015) and Sultan et al. (2017) found that the impact of these interventions was influenced by both the type of measurement and the agro-ecosystem under which it was implemented. Landscape, land use, soils, hydrological processes, and climate can be highly variable across regions, and their linkages to the success of environmental management practices are important aspects that must be understood and documented (Melesse and Abtew, 2016). In addition, Bayabil et al. (2010) illustrated that the effectiveness of a soil and water conservation practice depends on whether watershed runoff processes depend primarily on the local ecosystem, topography, or a combination of the two. The suitability of any soil and water management practice depends greatly upon the soil, topography, climate, cropping system, and resources available to farmers (Pathak et al., 2009). Overall, an agro-ecological approach can contribute substantially to sustainable intensification of agriculture, but this must supported by an improved knowledge of the optimal conservation measure for each combination of site type and land use (Lampkin et al., 2015).

In Ethiopia, the distribution and amount of rainfall show great spatial and temporal variation, which is strongly influenced by altitude (Rientjes et al., 2013; Schmidt and Zemadim, 2013; Fenta et al., 2017a). Bekele-Tesemma et al. (2005) suggested that temperature (which is determined by the altitude) and rainfall are the two most important climatic factors that affect land management from the point of view of farmers or development agents. Hurni et al. (2016) developed general soil and water conservation guidelines in which they noted that climate varies greatly within Ethiopia, which ranges from dry to wet, and covers a range of elevations from lowlands to highlands. As a result, it is not possible to apply the same soil and water conservation techniques everywhere. This conclusion was based on a feasibility study of different physical conservation measures that had been tested in micro-watersheds (soil conservation research sites) in different agro-ecology systems that had been monitored 25 years ago (Herweg and Ludi, 1999).

Gradually, a few agro-ecology based studies have emerged, but most focused on evaluation of the socioeconomic aspects (Kassie et al., 2009; Matouš et al., 2013; Schmidt and Zemadim, 2013; Hurni et al., 2015; Nigussie et al., 2017). Studies on the efficiency of soil and water conservation are few, and most concentrated on the combination of a single agro-ecology with a specific conservation measure (Taye et al., 2013; Adimassu et al., 2014; Amare et al., 2014; Dagnew et al., 2015; Fenta et al., 2017b; Sultan et al., 2017). However, these studies also lack detailed information about the hydrological dynamics created by the conservation efforts across a range of land use, cover types, and slope classes. Best management practice should encompass a series of measures that are useful, proven to be effective, cost-effective, and generally accepted among conservation experts and the ultimate users for specific agro-ecology systems. Hence, critical analysis of the runoff responses and efficiency of the available measures under different agro-ecology systems is needed to evaluate which particular sustainable land management interventions are most likely to be successful in a given location. This suggests a need for analyses that examine the interactions between various location-specific factors. The results of such observations will provide greater

insight into how soil and water conservation affects the hydrological processes under different agro-ecology systems. To provide some of the missing knowledge, we used plot-level runoff measurements and hydrological analyses at three different agro-ecological sites in the Amhara and Benishangul Gumuz administrative regions of Ethiopia. Our objectives were (1) to analyze the spatial variability of rainfall-runoff relationship and its controlling factors and (2) to determine the ability of different soil and water conservation practices to reduce runoff and improve soil moisture availability in typical agro-ecology systems in the Upper Blue Nile Basin of Ethiopia.

2 Materials and methods

2.1 Study area

We established experimental runoff plots to represent the different land use and cover types and different slope gradients at three experimental sites (Fig. 1): the Guder and Aba Gerima watersheds from the Fagita Lekoma (10°57′–11°11′N, 36°40′–37°05′E) and Bahir Dar Zuria (11°25′–11°55′N, 37°04′–37°39′E) districts, respectively, of the Amhara Region, and the Dibatie watershed from the Dibatie District (10°01′–10°53′N, 36°04′–36°26′E) of the Benishangul Gumuz Region. These sites were selected to represent three important agro-ecology systems in the Upper Blue Nile Basin having different annual precipitation, elevation, experiences with soil and water conservation, soil erosion rates, and land use types (Tables 1 and 2).

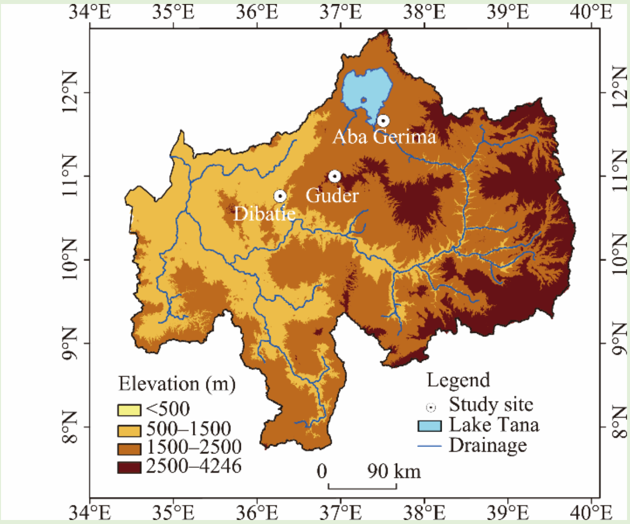

Fig. 1 Location of the study sites with different agro-ecology systems

Each study site has been part of the national government's regular extension programs and other public based soil and water conservation interventions, but the experiences of these study sites with other externally funded programs have varied greatly (Nigussie et al., 2017). The Aba Gerima watershed has been part of the Water and Land Resource Centre, which is funded by the Swiss Agency for Development and Cooperation, since 2011. The Guder watershed has received support for soil and water conservation initiatives from the World Bank under the Sustainable Land Management Programme since 2008. Dibatie has had no external funding support for conservation projects. The major but most common soil and water conservation measures implemented in the Upper Blue Nile Basin of Ethiopia are the creation of soil bunds (i.e., raised soil embankment from the ditch is moved downhill that block the flow of water), *Fanya juu* (i.e., raised soil embankment from the ditch is moved upslope), short trenches (i.e., excavating trenches along the contour at the hillside), and soil bunds combined with vegetation establishment to protect the soil (Haregeweyn et al., 2015; Fig. 2). Soil bunds and *Fanya juu* were constructed by building soil walls (about 0.5–1.0 m high) along the contour have similar dimensions of 1.6 m wide and 6.0 m

long with variable spacing depending on land use and slope. Soil faced short trenches were constructed by excavating trenches of 0.5 m deep, 1.4 m wide and 1.5–2.5 m long with spacing between trenches of 1.7 m along the contour.

Although the overall slope at each site does not change, the effective slope length (the distance between conservation structures) decreases; the principle is to reduce the speed of the flowing water when it contacts each structure and the volume of water that reaches the slope downhill of that structure, thereby reducing the runoff volume. Soil and water conservation measures are applied to even and uneven grounds in the Upper Blue Nile Basin by using different designs.

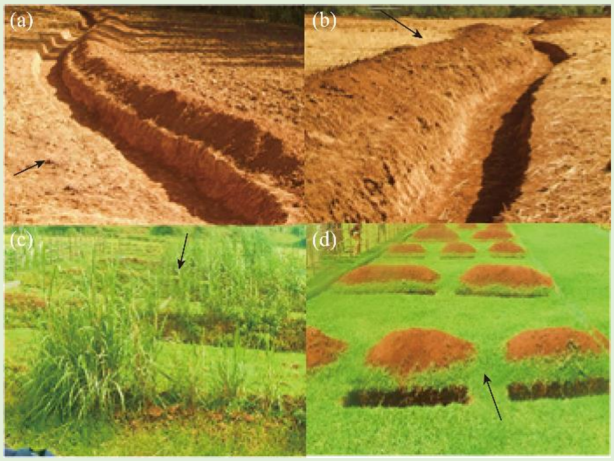

Fig. 2 Commonly implemented soil and water conservation measures for the major land use types in the three agro-ecology systems in the Upper Blue Nile Basin of Ethiopia. (a), soil bunds; (b), *Fanya juu* in cultivated land; (c), soil bunds combined with planting of vegetation (here, elephant grass) in cultivated land; and (d), short trenches in grazing land. The arrows indicate the slope direction.

2.2 Instrumentation and data collection

Each study site was equipped with a temperature sensor and datalogger (Mini-diver, Schlumberger Water Services, Netherland) and one manual rain gauge. The datalogger was programmed to measure the maximum and minimum air temperature at 10-min intervals. We screened this data by taking the maximum and minimum temperatures from 144 readings and calculated a daily average temperature, which we used to calculate potential evapotranspiration at each site. The rain gauge recorded daily rainfall in the rainy season from June to October 2015. More than 86% of the rainfall in the region is concentrated in these months (Sultan et al., 2017).

We measured runoff at the plot scale using a total of 42 runoff plots (30 m long×6 m wide each) in the three agro-ecology systems with 18 at Guder, 12 at Aba Gerima, and 12 at Debatie. We used four treatmentsfor the cultivated land on gentle and steep slopes; and two treatments for the non-agricultural land on steep slopes. Each agro-ecology system comprised cultivated land in two slope ranges (5% and 15%), grazing land (15% slope), and degraded bush (35% slope) plots. However; the Guder site had two additional main land use types, *Acacia decurrens* plantations (5% and 25% slopes), and *Eucalyptus* spp. plantations (25% slopes). We divided the plots into a group with gentle slopes (<15°) and a group with steep slopes (≥15°).

Each cultivated land plot had a different soil and water conservation treatment (soil bund, *Fanya juu*, soil bund with vegetation establishment, and a control without treatment). Each other non-agricultural land use types (grazing land, degraded bush, *A. decurrens* plantations, and *Eucalyptus* spp. plantations) each had two treatments (short trenches and control). Based on their availability of sufficient soil and plant species and the ongoing sustainable land management practices, details of the soil bund with vegetation establishment treatment varied among the sites. In the Guder cultivated land plots, the soil bunds were reinforced and stabilized by planting vegetation such as tree lucerne (*Cytisus proliferus*) and densho grass (*Pennisetum pedicellatum*) together, whereas elephant grass (*Pennisetum purpureum*) and vetiver grass (*Vetiveria zizanioides*) were planted at

the Aba Gerima and Debatie sites, respectively.

At the lower end of each plot, we excavated a 9.7-m^3 pit with a trapezoidal cross section (Fig. 3) and lined the pit with an impermeable geomembrane plastic to permit the collection of sediment and runoff. The pits were designed to accommodate the maximum runoff that would result from extreme rainfall events, predicted using the anticipated rainfall (based on historical records at the nearest meteorological station) and a runoff coefficient of 46% (Herweg and Ludi 1999; Haregeweyn et al., 2016). The runoff depth corresponding to each daily rainfall was recorded and used for our runoff analysis. An equation that related the water depth in the pit to the volume of the pit was established for each trapezoidal pit by adding a known volume of water. Then, based on this relationship, the runoff volume was calculated from runoff depth measurements taken every morning at around 08:00 am LST with a measuring tape at an average of six points in the pit to account for variations in water depth due to bottom irregularities. The effect of direct rain falling into the pit (estimated from the rain gauges) was subtracted from the total. The plots were also bounded at the sides to prevent inflows of runoff and sediment from the sides of the plot using sheets of corrugated metal inserted into the ground to a depth of 15 cm and protruding 20 cm above the ground (Fig. 3c). Finally, the runoff depth was calculated by dividing the net runoff volume collected from the pit to the runoff plot area.

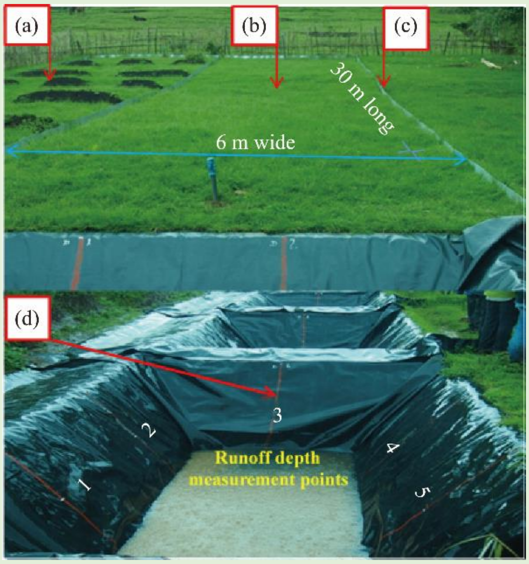

Fig. 3 Layout of the runoff plots established in grazing land in the Guder watershed. (a), plots with soil and water conservation measures; (b), plots without conservation measures; (c), corrugated iron sheets inserted in the ground to a depth of 15 cm to establish the plot boundaries; (d), runoff collection pit lined with impermeable geomembrane plastic. Water depth was measured at the six numbered points (1–6) on the liner (Sultan et al., 2017), with the point No. 6 in the opposite side of No. 3.

The values of various soil variables were determined to characterize each site (Table 1). Three samples were taken from the top 30 cm of the soil profile at intervals of 10 cm for each land use type and analyzed to determine the texture using the hydrometric method (Sheldrick and Wang, 1993) and the average of the particle-size distributions were used to characterize the site. Undisturbed soil samples were taken to a depth of 30 cm at 10-cm intervals using a core sampler with a volume of 100 cm^3 to determine the soil bulk density to determine the bulk density. The samples were then oven-dried at 105 ℃ for 24 h and weighed. The bulk density was determined by dividing the weight of the oven-dried soil samples by the volume of the soil core. Soil penetration resistance (SPR (kPa)) was measured by using a hand-operated soil cone penetrometer (Hand penetrometer, Eijkelkamp Company, the Netherlands) with a cone (2-cm^2 base size) and a driving shaft graduated at 5-cm intervals. For each site, we calculated the SPR as the average of

30 observations.

Table 1 Main characteristics of research sites

Characteristics	Dibatie	Aba Gerima	Guder
Mean elevation (m a.s.l.)	1490 Lowland	1998 Midland	2728 Highland
Mean daily temperature (℃)	18–29	17–31	15–24
Mean annual precipitation (mm)	1022	1343	2495
Major soil texture class	Clay	Clay	Clay loam
Soil types	Vertisols, Nitosols	Nitosols, Leptosols	Acrisols, Nitosols
Soil bulk density (g/cm^3)	1.11–1.44	1.21–1.40	0.83–1.34
Average soil penetration resistance (kPa)	2400	2200	1639
Agro-ecology zone[a]	Tropical hot humid (Moist Kolla)	Humid subtropical (Moist Weyna Dega)	Moist subtropical (Wet Dega)
Dominant crops[b]	Finger millet, teff, maize, groundnut	Teff, finger millet, wheat, maize, khat	Barley, teff, wheat, potatoes
Soil erosion severity[c]	Slight	Moderate	Very severe
Rainfall erosivity	High	Very high	Very high
Soil and water conservation activities	Low	High	Medium

Note: Moist Kolla, 500–1500 m a.s.l., mean annual precipitation of 900–1400 mm; Moist Weyna Dega, 1500–2300 m a.s.l., mean annual precipitation of 900–1400 mm; Wet Dega, 2300–3200 m a.s.l. and mean annual precipitation of ≥1400 mm (Hurni et al., 2016; Nigussie et al., 2017); Slight, 5–15 Mg/(hm^2•a); Moderate, 15–30 Mg/(hm^2•a); Very severe, ≥50 Mg/(hm^2•a) (Haregeweyn et al., 2017). [a], Sultan et al. (2017); [b], Nigussie et al. (2016); [c], Ebabu (2016).

Table 2 summarizes the characteristics of the soil and water conservation measures implemented in the runoff plots. The slope of the plot was measured with a clinometer (PM-5/360 PC Clinometer, Suunto, Finland). The dimensions of each conservation measure were based on the standard practices in the study area. The short trenches were installed in two rows across the slope by excavating the soil to a depth of 0.5 m: the upslope row comprised shorter lengths (1.4 m×1.5 m) separated by 0.5 m and the downslope row comprised longer lengths (1.4 m×2.5 m for the *A. decurrens*, grazed grassland, *Eucalyptus* spp., and degraded bush sites; 1.6 m×6.0 m for the cultivated sites; Table 2). The long and short axis of the excavations were oriented perpendicular to the slope.

2.3 Data analysis

We analyzed the plot data for seasonal runoff, runoff coefficient (RC), runoff conservation efficiency (RCE), and seasonal soil moisture availability. We quantified the relationships between daily rainfall and runoff depth by means of regression analysis. RC was calculated by Equation 1.

$$\mathrm{RC} = (\text{Runoff depth} / \text{Rainfall depth}) \times 100\% . \tag{1}$$

Runoff conservation efficiency (RCE) in each plot was calculated relative to runoff in the corresponding control plot using Equation 2 (Herweg and Ludi, 1999; Sahoo et al., 2016).

$$\mathrm{RCE} = \frac{(A-B)}{A} \times 100\% , \tag{2}$$

where A is the runoff loss (mm) from the control plot and B is the runoff loss (mm) from the corresponding plot with a conservation measure.

Seasonal moisture conservation efficiency was measured by the change in seasonal water availability analyzed for all runoff plots using the water-balance equation (Eq. 3; Dingman, 2015).

$$\Delta S = P - Q - \mathrm{ET} , \tag{3}$$

where ΔS (mm) is the seasonal change in moisture stored in the soil (including deep percolation beyond the soil zone); P is the seasonal precipitation (mm); Q is seasonal measured runoff (mm); and ET is seasonal evapotranspiration (mm). Since accurate field measurements are often difficult to acquire, evapotranspiration is usually estimated as the potential evapotranspiration (PET). Given the limited long-term meteorological data available for the study watersheds, we used the

temperature-based method (Eq. 4) developed by Hargreaves and Samani (1985) to calculate PET.

$$\mathrm{PET} = 0.0023 \times R_a \times \left[\frac{T_{\max} + T_{\min}}{2} + 17.8\right] \times \left(T_{\max} - T_{\min}\right)^{0.5}, \tag{4}$$

where R_a is the solar radiation (mm/day) estimated based on the approach suggested by Allen et al. (1998); T_{max} is the daily maximum temperature (℃) and T_{min} is the daily minimum temperature (℃).

Table 2 Characteristics of the 30 m×6 m runoff plots used to study the effects of land use and soil and water conservation (SWC) practices on runoff in Ethiopia

Land use type	SWC treatment	Slope	Spacing	Dimension of SWC structure		Number of SWC per plot	Number of plots per land use type×slope group		
		(%)	(m)	Short (m)	Long (m)		Guder	Aba Gerima	Debatie
CL1	Control	5	–	–	–	0	4	4	4
	Soil bund		7.8	–	1.6×6.0	3			
	Fanya juu		7.8	–	1.6×6.0	3			
	Soil bund		7.8	–	1.6×6.0	3			
CL2	Control	15	–	–	–	0	4	4	4
	Soil bund		5.5	–	1.6×6.0	4			
	Fanya juu		5.5	–	1.6×6.0	4			
	Soil bund		5.5	–	1.6×6.0	4			
AD1	Control	5	–	–	–	0	2	–	–
	Short trench		2.9	1.4×1.5	1.4×2.5	15			
AD2	Control	25	–	–	–	0	2	–	–
	Short trench		1.7	1.4×1.5	1.4×2.5	20			
GR2	Control	15	–	–	–	0	2	2	2
	Short trench		1.7	1.4×1.5	1.4×2.5	20			
EP2	Control	25	–	–	–	0	2	–	–
	Short trench		1.7	1.4×1.5	1.4×2.5	15			
DB2	Control	35	–	–	–	0	2	2	2
	Short trench		1.7	1.4×1.5	1.4×2.5	20			

Note: CL, cultivated land; DB, degraded bush; AD, *Acacia decurrens* plantation; EP, *Eucalyptus* spp. plantation; GR, grazing land; 1 and 2 followed the land use types means gentle slope and steep slope, respectively. 0 indicates no soil and water conservation structure; –, not applicable; *Fanya juu*, a Swahili word meaning 'throw uphill'.

3 Results and discussion

3.1 Runoff variability within and between agro-ecology systems

Table 3 summarizes the cumulative rainfall and cumulative runoff during the rainy season, RC, and RCE for all plots. The seasonal rainfall totaled 1568 mm for Guder, 1402 mm for Aba Gerima, and 881 mm for Debatie. The seasonal runoff from control plots in the Guder watershed ranged from 214 to 560 mm, versus 253 to 475 mm at Aba Gerima and 119 to 200 mm at Debatie. The highest runoff was 560 mm, in grazing land control plots on steep slopes at Guder (GR2), and the lowest was 81 mm, in short trench plots on steep slopes at Debatie (DB2). The cumulative runoff was the lowest at Debatie, which was the site with by far the lowest precipitation. Changes in precipitation regimes clearly have the potential to profoundly affect runoff and soil erosion. Lee et al. (1996) confirmed that the precipitation had a linear relationship with runoff and soil erosion, with little difference in runoff response to a change in storm frequency or intensity. The grazing land site on a steep slope (GR2) generated the highest seasonal runoff at Guder (560 mm), followed by the same site type at Aba Gerima (475 mm) and Debatie (134 mm); the high runoff in Guder might be related to frequent trampling by animals because the site was used for grazing livestock. As a result, we found compacted topsoil surfaces in grazing lands, with the highest soil penetration resistance (SPR ranging from 1990 to 2210 kPa), versus a maximum of 1100–1660 kPa for the other land use types.

This reduced infiltration and thereby increased runoff. A similar analysis for the Upper Blue Nile Basin showed that cattle on wet grazing soils caused additional compaction in the top 30 cm soil layers (Tebebu et al., 2015), leading to higher runoff production.

Table 3 Runoff conservation efficiency (RCE) and runoff coefficient (RC) for the different land use types and different SWC practices in the three agro-ecology systems during the rainy season from June to October 2015

Site	Land use type×slope group	SWC treatment	Cumulative rainfall (mm)	Cumulative runoff (mm)	Runoff conservation efficiency (%)	Seasonal RC (%)
Guder	CL_{av}	Control	1567.6±13.4	401.0±1.6	–	26.00
		Soil bund		272.4±1.5	32.1	17.41
		Fanya juu		264.3±1.6	34.1	16.91
		Soil bund		271.7±1.8	32.2	17.30
	GR2	Control		560.4±4.2	–	35.70
		Short trench		313.4±2.1	44.0	20.00
	DB2	Control		214.3±1.8	–	13.70
		Short trench		157.5±1.4	27.0	10.00
	AD_{av}	Control		396.0±5.1	–	25.30
		Short trench		211.3±1.8	47.0	13.53
	EP2	Control		217.4±2.2	–	13.83
		Short trench		155.5±2.0	28.0	10.00
Dibatie	CL_{av}	Control	881.2±11.7	199.7±3.0	–	22.70
		Soil bund		103.4±1.2	48.0	11.70
		Fanya juu		105.4±1.2	47.0	12.00
		Soil bund		97.3±1.2	51.0	11.00
	GR2	Control		134.4±2.6	–	15.30
		Short trench		101.5±1.8	25.0	11.50
	DB2	Control		119.4±2.3	–	13.60
		Short trench		81.4±1.2	32.0	9.20
Aba Gerima	CL_{av}	Control	1401.5±13.7	253.3±4.0	–	18.00
		Soil bund		158.1±3.2	38.0	11.30
		Fanya juu		165.6±2.5	35.0	11.80
		Soil bund		163.4±2.6	36.0	11.70
	GR2	Control		475.0±7.2	–	40.00
		Short trench		213.8±2.6	55.0	15.30
	DB2	Control		275.5±3.9	–	19.70
		Short trench		151.8±2.1	45.0	10.80

Note: Cl_{av}, average for cultivated land in both slope classes (CL1 and CL2 in Table 2); AD_{av}, average for *A. decurrens* plantations in land with gentle and steep slopes; –, not applicable. Mean±SD.

Although higher surface runoff is expected from control plots on steeper slopes (35%), surface runoff from plots with degraded bush was lower than that from the other land use types, except for cultivated land at Aba Gerima (Table 3). This can be explained, on the one hand, by the direct effect of raindrop interception by the vegetation canopy, which dissipates their energy and creates infiltration pathways (Morgan et al., 1986; Castillo et al., 1997; Descroix et al., 2001). On the other hand, vegetation decreases runoff indirectly by improving soil physical properties through the incorporation of organic matter (16.7% in Guder; Sultan et al., 2017) and loosening of the soil by growing roots, thereby increasing the infiltration rate (Descheemaeker et al., 2006). Taye et al. (2013) explained this in a different way; they reported that RC decreased with increasing slope due to an increase in the content of coarse particles in the soil, which promoted infiltration. Similarly, Tebebu et al. (2015) illustrated that, for saturation-excess runoff, water infiltrates on hillsides and erosion-inducing runoff occurs in the flatter, downslope parts of landscapes. This, in turn, affects the hydrology, since excess water flows more rapidly to valley bottoms as lateral flow, leading to gully formation (Bayabil et al., 2010). All of these factors may have combined to overwhelm the

slope effect.

3.2 Variability of rainfall-runoff responses within and across the three agro-ecosystems

Taking into account the interactions between the soil and water conservation measures and the two dominant land use types, which were cultivated land on steep slopes (CL2) and grazing land (GR2), we calculated the rainfall thresholds required to generate runoff for both of these at each agro-ecology system (Fig. 4; Table 4). The threshold rainfall can be determined by plotting the daily runoff depth against the corresponding rainfall depth (Fig. 4) and performing least-squares regression (Descheemaeker et al., 2006; Girmay et al., 2009). The slope of the regression line represents how rapidly runoff depth increases with increasing rainfall depth after the rainfall threshold is exceeded. The threshold rainfall values were selected based on the probability of 80% of events below the threshold level rainfall failing to produce runoff. The higher the rainfall threshold and the lower the slope of the curve, the higher the infiltration rate and greater the storage capacity of the soil in the agro-ecology system (Descheemaeker et al., 2006; Girmay et al., 2009).

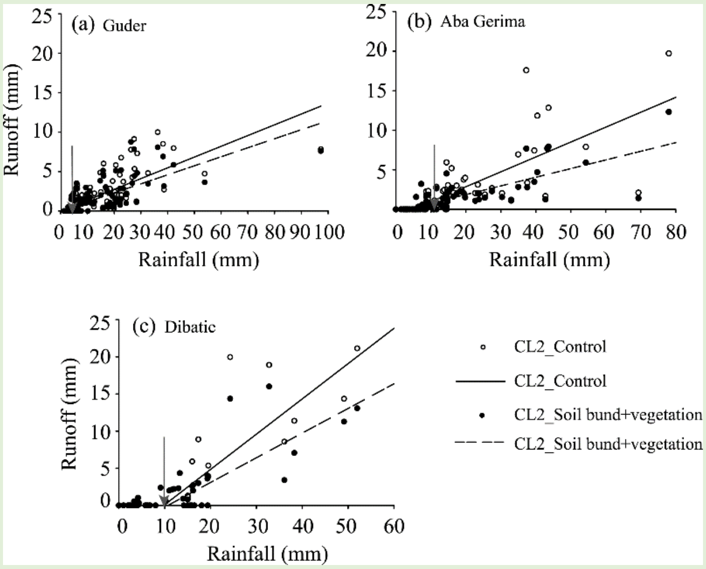

Fig. 4 Regressions of runoff as a function of rainfall (excluding the events that produced no runoff) and its use to determine the rainfall thresholds (arrows) for six plot types: CL2_Control, cultivated control plots on steep slopes; CL2_Soil bund+vegetation, cultivated plots on steep slopes with a soil bund combined with vegetation establishment.

The biggest rainfall event at Guder was 97 mm, versus 78 mm at Aba Gerima and 53 mm at Debatie. In the Guder watershed, the rainfall threshold values for runoff generation were 6 and 5 mm in cultivated land (CL2) and grazing land (GR2) on steep slopes, respectively (Table 4). For the same land use types, the largest rainfall threshold values were obtained at the Dibatie and Aba Gerima sites, with thresholds of more than 10 and 9 mm, respectively. The slope of the rainfall-runoff curve also varied widely among the plots; with the values of 0.10–0.45. The soil and water conservation practices using vegetated soil bunds and short trenches in the cultivated and grazing land plots resulted in a lower slope of the curve than in the corresponding control plots at all three sites (Table 4). This can be attributed to storage of runoff in depressions and slowing of the runoff flow by the conservation structures.

The response of runoff to rainfall at the moist subtropical site (Guder) began sooner (i.e., a lower rainfall threshold) than that at the humid subtropical (Aba Gerima) and the tropical hot humid (Debatie) sites (Table 4). Sultan et al. (2017) reported that Guder receives long-lasting rainfall events with small amounts of rainfall, and yet that this site has a longer rainy season than other sites in the western and central highlands; nonetheless, the higher proportion of rainfall (63%) that comes from light rainfall events, which influences subsequent availability of soil moisture. In

addition, the heavy soils of the Guder watershed (Table 1) tend to retain moisture for a longer period, and this can lower the threshold rainfall compared with other sites. Therefore, small increases in precipitation could result in waterlogging and damage to soil and water conservation structures if subsequent precipitation occurs as intense storms that deposit more rain than the threshold value.

On average, the rainfall threshold values at our study sites are higher than those in semi-arid regions of northern Ethiopia (the Tigray region). For example, Descheemaeker et al. (2006) obtained rainfall threshold values ranging from 3 to 16 mm in plots with different land use types. Similarly, Girmay et al. (2009) reported that rainfall events >2 mm produced runoff in cultivated land, whereas rainfall events >3 mm produced runoff in both grazing land and plantation areas. This illustrates the lower interception capacity of vegetation canopies at semi-arid sites and the lower infiltration capacity of soils in drier environments (Pilgrim et al., 1988). It is worth noting that the experimental plot dimensions (5 m×2 m and 10 m×2 m in the previous studies, both of which were much smaller than the dimensions in the present study) can strongly affect the results of such studies, as the runoff amount is strongly influenced by scale effects (Bergkamp, 1998).

Table 4 Rainfall threshold (*T*) required to generate runoff, and slope of the rainfall-runoff curve for each plot at the three study sites.

Site	Plot code	SWC treatment	T (mm)	Slope	R^2	*n*
Guder	CL2	Control	6	0.107	0.35*	70
	CL2	Soil bund		0.097	0.37*	70
	GR2	Control	5	0.062	0.03*	75
	GR2	Short trench		0.041	0.03*	75
Aba Gerima	CL2	Control	11	0.182	0.41*	45
	CL2	Soil bund		0.109	0.45*	45
	GR2	Control	9	0.412	0.38*	46
	GR2	Short trench		0.128	0.34*	46
Debatie	CL2	Control	10	0.450	0.67*	36
	CL2	Soil bund		0.310	0.53*	36
	GR2	Control	9	0.298	0.62*	38
	GR2	Short trench		0.188	0.59*	38

Note: *n*, number of observations; *, regression significance at $P<0.05$ level.

3.3 Effects of soil and water conservation measures on RC and RCE

The percentage of seasonal rainfall lost as runoff from control plots in the Guder watershed ranged from 14% to 36%, versus 18% to 40% at Aba Gerima and 14% to 23% at Dibatie (Table 3), demonstrating the high variability of RC across the three studied environments. RC also differed between the control and treatment plots at each site.

Monthly RC was the highest in July and August in most treatments and decreased during September and October at all sites (Fig. 5). This can be explained by decreasing rainfall at the end of the rainy season combined with increasing vegetation cover during the rainy season, which would decrease runoff generation.

The knowledge provided by the present study about the RC of various land use types under different agro-ecology systems is essential to support estimates of runoff from a given watershed under a given land use. This, in turn, can help land managers to design appropriate water-harvesting structures, such as drainage canals, waterways, and reservoirs, and to predict flood hazards (Adimassu and Haile, 2011; Haregeweyn et al., 2016).

At the Guder site, the RCE of the soil and water conservation measures ranged from 27% to 47%, versus 25% to 51% at Dibatie and 35% to 55% at Aba Gerima (Table 3). In general, the highest RCE was obtained for plots treated with soil bunds combined with vegetation establishment

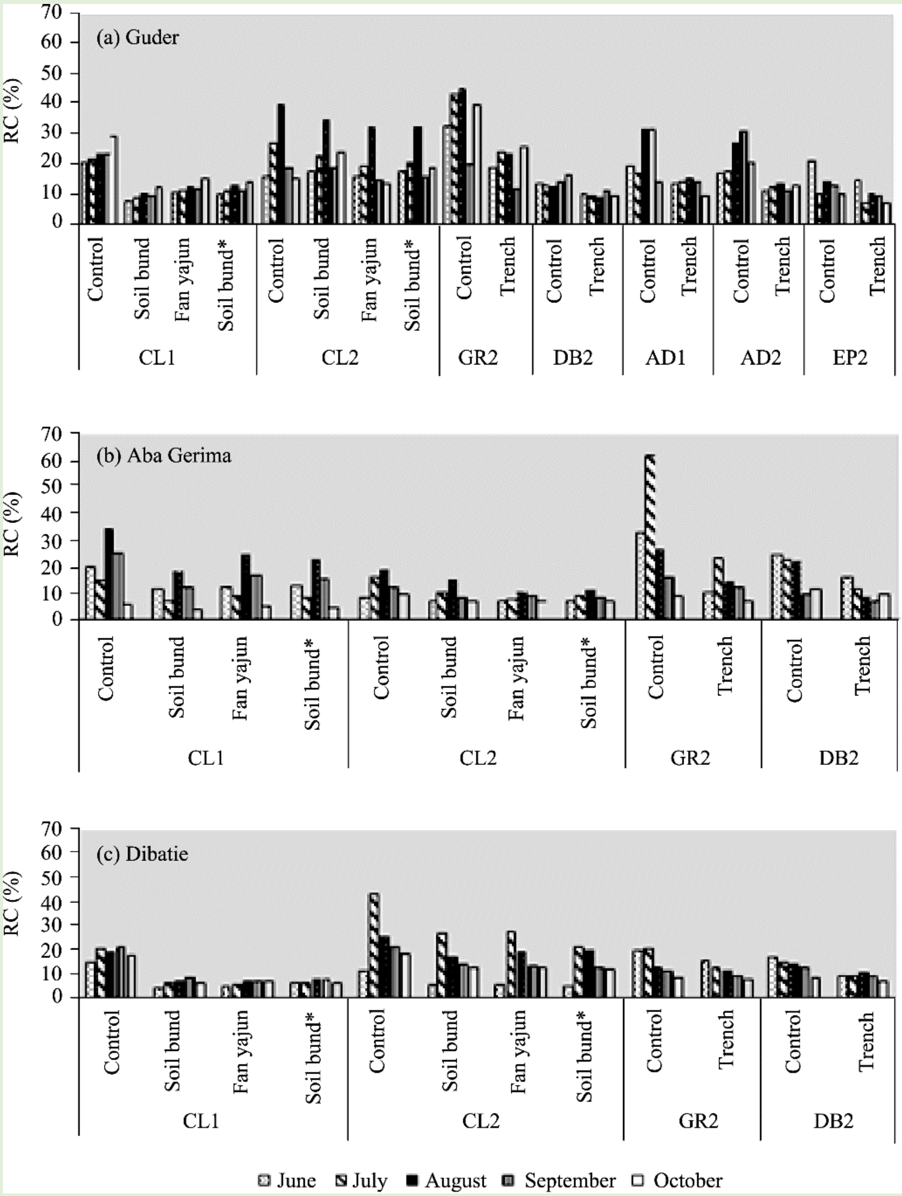

Fig. 5 Seasonal patterns of runoff coefficient (RC) values (%) under different combinations of soil and water conservation measures and combinations of land use type. CL, cultivated land; GR, grazing land; AD, *A. decurrens* plantation; EP, *Eucalyptus* spp. plantation; DB, degraded bush; 1, gentle slope; 2 steep slope; *, soil bund combined with vegetation establishment.

based on the average for cultivated land. The soil bunds combined with vetiver grass (*V. zizanioides*) at Debatie were more effective (RCE, 51%) than those with tree lucerne (*C. proliferus*), densho grass (*P. pedicellatum*; RCE, 32%) and elephant grass (*P. purpureum*; RCE, 36%). In contrast, Amare et al. (2014) obtained the lowest runoff values for soil bunds combined with elephant grass, followed by soil bunds combined with the legume species *Tephrosia* in the northwestern Ethiopian highlands, and they also suggested that vetiver grass required a longer establishment period before it could begin to conserve soil and water efficiently. For the plots in non-agricultural land, the highest RCE (55%) was obtained in GR2 plots treated with short trenches at the Aba Gerima site. On average, the establishment of soil and water conservation measures decreased runoff by 35%, 41%, and 42% at the Guder, Debatie, and Aba Gerima sites, respectively.

Thus, there is strong evidence that the adoption of soil and water conservation practices can reduce runoff more in areas with low rainfall than in areas with high rainfall. This is because dry soils have higher infiltration capacity than wet soils during the rainy season.

Higher RCE was obtained in all treatments in plots with a gentle slope than in the comparable treatment in plots with a steep slope due to the greater difference in runoff between the treated and control plots. In general, creating short trenches and soil bunds combined with vegetation establishment produce better runoff reduction than the other practices, especially in grazing land and cultivated land.

3.4 Effects of soil and water conservation on soil moisture availability

The combination of the distinctive features of the agro-ecology system, of the soil and water conservation practices, and of the associated hydrological processes affected the seasonal water availability in the plots (Fig. 6). The seasonal potential evapotranspiration values were 579, 675, and 732 mm for the Guder, Dibatie, and Aba Gerima sites, respectively, which were determined by the Hargreaves and Samani (1985) equation. The soil water availability (Fig. 6) obtained by means of the water-balance method ranged from 428 to 830, 394 to 515, and 7 to 124 mm for the Guder, Aba Gerima, and Dibatie sites, respectively. The differences in these ranges can be attributed to differences in the frequency of rainfall (amount), soil type, runoff amount (Table 3), and potential evaporation among the different agro-ecology systems. On average, implementation of soil and

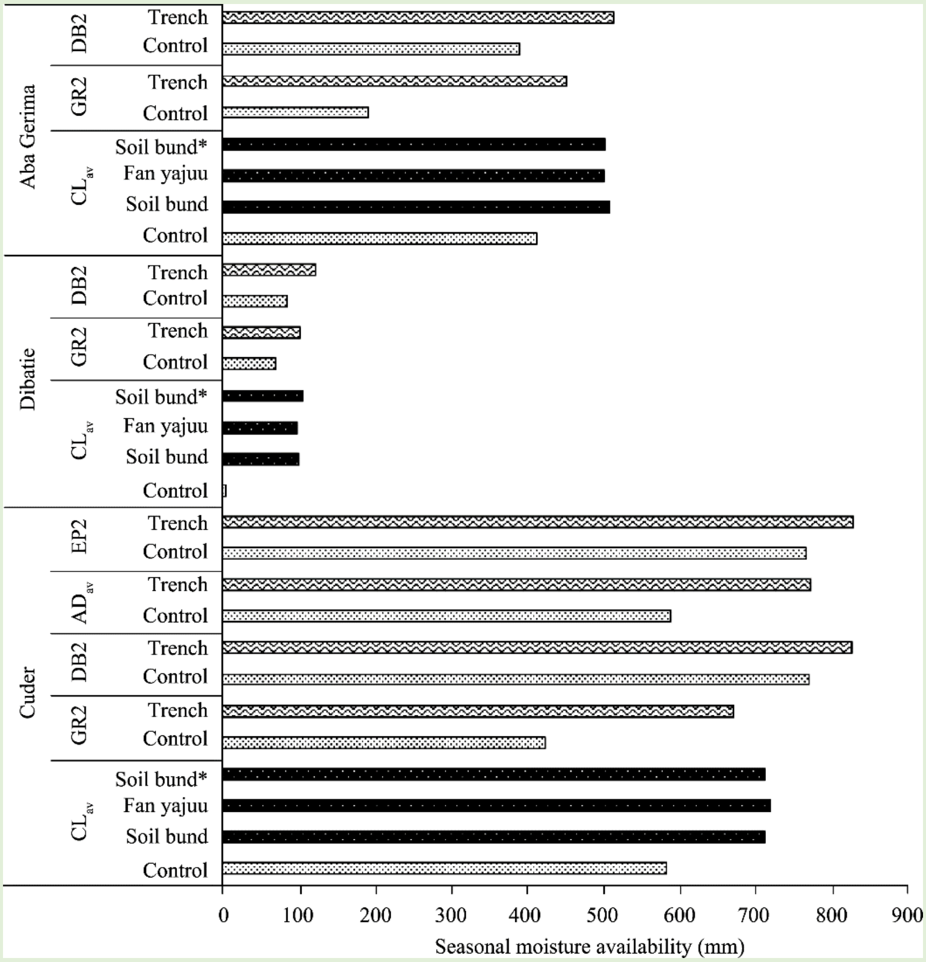

Fig. 6 Comparison of the effects of the different SWC practices on water availability during each month of the rainy season for the different agro-ecology systems. Cl_{av}, average for cultivated land in both slope classes (CL1 and CL2 in Table 2); AD_{av}, average for *A. decurrens* plantations in land with gentle and steep slopes.

water conservation measures increased seasonal water availability by about 139 mm compared with the control plot at the Guder site, versus 130 and 67 mm at the Aba Gerima and Debatie sites, respectively (Fig. 6). This indicates that the infiltration and runoff dynamics were also influenced by slope length, because the reduction of slope length caused by installation of the conservation structures increased storage and thereby reduced the volume of runoff.

Our results indicated that areas with higher rainfall (e.g., Guder) had higher potential soil moisture, and therefore a lower rainfall threshold to generate runoff. This decreased the conservation efficiency of the various soil and water conservation practices (Table 3). Consequently, the role of management practices was more important. It is more necessary to choose and design the optimal structure for these sites, i.e., where there is more runoff, there is more sediment transport capacity. Hence to control erosion and offsite transport of sediment, soil and water conservation planers need to focus on the safely disposal of the runoff to avoid risk of crop damage due to flooding or increase opportunities for sediment deposition from overland flow. This understanding helps to balance the soil erosion effect against the moisture retention/shedding effects of different measures.

Herweg and Ludi (1999) illustrated that runoff control requires a careful consideration of the design of soil and water conservation structures in relation to site characteristics. For example, in sub-humid or wetter areas with high rainfall, managers must prioritize both soil conservation and drainage of excess water. In addition, Nyssen et al. (2004) reported that in wet areas, investments in soil and water conservation may not be profitable at the farm level, although there are positive social benefits from controlling runoff and soil erosion at a regional level.

Although many of the methods discussed in this paper have been tried in the study area, they have not been widely adopted and have sometimes been dis-adopted where they were tried. To solve these problems, it will be necessary for the government and other stakeholders to increase knowledge transfer (extension) services to demonstrate the successful use of the techniques. In addition, the conservation structures all require ongoing maintenance. This agro-ecological classification and its related information assists in utilizing the research and field experience of one place to other places of identical soil, climatic and topographic conditions.

4 Conclusions

In this study, we provided an overview of the hydrological dynamics and effectiveness of soil and water conservation practices to reduce runoff under the common agro-ecology systems in the Upper Blue Nile Basin of Ethiopia. These results can guide managers towards the optimal choice of soil and water conservation measures under specific site conditions. Our study revealed that the responses of runoff and runoff conservation efficiency to soil and water conservation practices were highly variable both within and between agro-ecology systems. This high variation could be attributed to a combination of several factors such as the type of soil (permeability), land use types, soil water availability, the response of runoff to rainfall, and the prevailing climatic conditions (precipitation and potential evapotranspiration). These practices were highly effective in controlling runoff in the humid subtropical (Moist Weyna Dega) and tropical hot humid (Moist Kolla) agro-ecology systems, with average runoff reductions of 42% and 41%, respectively. The moist subtropical region (Guder) had a higher potential soil moisture availability, but a lower rainfall threshold to generate runoff. From these findings, implementation of short trenches (humid subtropical) in grazing land maximized the efficiency in conserving runoff (55%) due to temporary water storage in the short trenches, followed by infiltration. In contrast, vegetated bunds would be most effective in cultivated land, and short trenches would be effective in the two plantation types. Our results demonstrate the importance of studying each combination of agro-ecology system, site, and climate to scientifically determine the optimal conservation measures for that combination instead of making blanket recommendations for all systems that are likely to provide suboptimal results for many combinations. This understanding and the present results will help managers to choose the most effective conservation measures based on field trials and to test whether they will be equally applicable at other locations with similar soil, climatic, and topographic conditions.

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